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RADIATION CONTAMINATION OF DIELECTRICS IRRADIATED WITH A FAST-ELECTRON FLUX

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It is known that, in irradiating dielectrics and semiconductors with a fast-electron flux, they accumulate a space charge (SC), the electric field of which affects considerably the transport of primary particles, while it can also cause electric breakdown and disintegration of the dielectric [1-3]. Although this phenomenon has been investigated intensively during the past 20 years, a satisfactory mathematical description of it is still lacking, which sometimes hampers the interpretation of experimental data. The principal approximation inherent in the known solutions of the problem of SC dynamics [2, 4] consists in neglecting the distortion of the absorbed energy and thermalized electrons caused by the effect of the SC field on transport.

We have devised and realized a nonstationary mathematical model which describes in a self-consistent manner the SC build-up and the transport of fast electrons for different boundary conditions.

System of Equations. The mathematical model describing the space charge build-up in the dielectric is based on the phenomenological model [4]. In order to take into account the distortion in the distribution of absorbed energy and thermalized electrons due to the effect of the electric field on the past particle transport, the equations of space charge kinetics were supplemented with the kinetic equation accounting for the electric field for fast electrons. In the one-dimensional case, the system of equations has the following form:

$$\frac{\partial N}{\partial t} = Q_e + S - \alpha PN - \frac{\partial J_N(N, E)}{\partial z}; \quad (1)$$

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$$\frac{\partial P}{\partial t} = S - \alpha PN - \frac{\partial J_P(P, E)}{\partial z}; \tag{2}$$

$$\frac{\partial E}{\partial z} = \frac{e}{\varepsilon\varepsilon_0}(P - N); \tag{3}$$

$$\hat{L}\psi + E\hat{F}\psi = S_\psi; \tag{4}$$

$$Q_e = -e\int_{4\pi} d\Omega \int_{T_p}^{T_m} dT\psi(z, u, T)\int_0^{T_p} dT'\Sigma_i(T \to T'); \tag{5}$$

$$\dot{D} = \int_{4\pi} d\Omega \int_{T_p}^{T_m} dTB(T)\psi(z, u, T), \quad S = \dot{D}/\omega_i. \tag{6}$$

Here, N and P are the total concentrations of electrons and holes, including both quasi-free and captured charge carriers, Q_e is the thermalization rate of fast electrons, S is the generation rate of electron–hole pairs due to the ionization of the medium, $\alpha = \tilde{\alpha}_N\Theta_N + \tilde{\alpha}_P\Theta_P$ is the effective recombination coefficient, $\tilde{\alpha}_N$ and $\tilde{\alpha}_P$ are the microscopic recombination coefficients, averaged with respect to the velocities of the negative and the positive carriers, Θ_N and Θ_P are the percentages of quasi-free electrons and holes, $J_N = \mu_N NE$ and $J_P = \mu_P PE$ are the currents due to the motion of electrons and holes, $\mu_{N,P} = \tilde{\mu}_{N,P}\Theta_{N,P}$ are the effective electron and hole mobilities, $\tilde{\mu}_N$ and $\tilde{\mu}_P$ are the actual mobilities of quasi-free electrons and holes, $\hat{L}$ is the transport operator accounting for the elastic and inelastic scattering processes [5], $\hat{F} = e\left[u\frac{\partial}{\partial T} + \frac{1}{p_e v_e}\frac{\partial}{\partial u}(1 - u^2)\right]$ u = cos ϑ; ϑ is the angle between the electron momentum p_e and the z axis, v_e is the electron velocity, e is the elementary charge, T is the kinetic energy, ψ is the electron flux density, which is differential with respect to angles and energy, S_ψ is the function of the fast electron source, E is the strength of the electric field, Σ_i is the macroscopic cross section of inelastic scattering, T_m is the upper limit of the electron spectrum, T_p is the threshold energy below which electrons are assumed to be thermalized (in our calculations, $T_p = 0.02T_m$); B(T) is the specific energy loss of fast electrons, and ω_i is the mean energy of ion formation.

In the above model, the dependence of the material parameters α and μ on the radiation characteristics is comprised in $\Theta_{N,P}$ – the percentage of one-type, quasi-free carriers of the over-all number of carriers, including those captured in traps. Therefore, in order to solve Eqs. (1)-(6), it is necessary to adopt certain model concepts regarding Θ and also the boundary conditions for the current in Eqs. (1) and (2) and the boundary conditions for the field (the potential) in (3). The initial conditions are chosen in the following form: $P(t = 0) = N(t = 0) = 0$.

Generally, Θ_N and Θ_P depend on the trap spectrum, the irradiation dose rate, and the negative and positive charges captured in traps.

In the early research into the charge build-up in dielectrics irradiated in an electron beam [4, 6], it was postulated that Θ_N is independent of the irradiation time and is determined by the dose rate. This made it possible to obtain good agreement with experimental data for polymethyl methacrylate (PMMA) [7]. The model proposed in [4] was refined in subsequent work, and a dependence of Θ_N at thermodynamic equilibrium for the exponential trap spectrum on the space charge and the dose rate $\dot{D}$ was obtained in [8] for different sets of build-up conditions. This dependence contains the parameter $\Delta = T_1/(T_1 + T)$, where T_1 is the characteristic temperature in the trap distribution with respect to energy, and T is the temperature. In this case, $\mu_{N,P} = \mu_{N,P}^{(0)}(\dot{D}/D_0)^{2\Delta-1}$ ($\mu_{N,P}^{(0)}$ and D_0 are constants [1]). In particular, for $\Delta = 0.5$, $\Theta_{N,P}$ is always independent of the space charge. It should be mentioned that the investigations in [7] were performed on PMMA for which the value of Δ was close to 0.5 [9], which allowed proper interpretation of the experimental results. For further refinement of the model proposed in [8], it is necessary to consider the time dependence of $\Theta_{N,P}$ under injection conditions and estimate the time for the establishment of thermodynamic equilibrium. Such a problem was solved numerically in [10] for a dielectric with the characteristic parameters, where it was found that the time for $\Theta_{N,P}$ to reach a steady-state value was equal to $\sim 10^{-3}$ sec. Under continuous irradiation, when the build-up time amounts to tens or more seconds, the time dependence of $\Theta_{N,P}$ can be neglected.

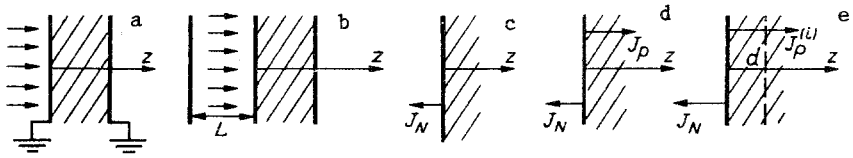

Fig. 1

Boundary Conditions. The standard boundary conditions are used for the differential flux density ψ [5]. The two most important cases of dielectric irradiation must be considered in assigning the boundary conditions for the J_N and J_P currents and the field: dielectric irradiation with the boundary conditions assigned for the potentials and irradiation of a dielectric with an exposed surface. The first case is realized when the surfaces of the dielectrics are covered by conducting electrodes (Fig. 1a), while the second case is realized when there is an electrode only on the unirradiated side of the dielectric (Fig. 1b).

In accordance with [1], we shall consider three types of boundary conditions for the current through the surface of a dielectric with an electrode. Boundary conditions of the first type specify blocking electrodes, which prevent the transmission of charge carriers from the electrode to the interior of the dielectric, but receive charge carriers from it (Fig. 1c). As a rule, metal electrodes obtained by spray-coating in a vacuum, located on the unirradiated surface of the dielectric, are characterized by such properties. Boundary conditions of the second type provide for ohmic (or neutral) electrodes which ensure charge transmission in the direction determined by the electric-field vector in the dielectric near its surface. During the specimen's irradiation, the blocking electrode may become ohmic. Boundary conditions of the third type specify an injecting electrode, whose behavior resembles that of a cathode with infinite emissivity, which ensures the electric field E = 0 at the electrode (Fig. 1e). Boundary conditions of this type occur in the case of an electrolytic electrode or in the case of contact between the dielectric and a plasma. The expression for the injection current $J_p^{(i)}$ in the case of electron irradiation of a dielectric can be obtained by assuming that, in a small region ($z \leq d$, $d \ll a$; a is the thickness of the dielectric layer), $p \gg N$, and $J_p^{(i)} \gg J_N$. Then, solving Poisson's equation for the $0 \leq z \leq d$ region and joining this solution to the solution of Poisson's equation for the remaining region of the dielectric and using the condition E(0) = 0, we obtain

$$J_P^{(i)} = \varepsilon\varepsilon_0 \frac{\mu_P}{2}\left(\frac{(a-d)\,E_d^0 - V}{(a-d/3)\,d}\right)^2, \tag{7}$$

where V is the potential difference applied to the dielectric, and $E_d^{(0)}$ is the field in the z = d plane, found by solving Poisson's equation in the z > d region for zero boundary conditions.

Let us now determine the boundary conditions for the current and the potential in irradiating a dielectric with an exposed surface. Assume that a plane with the potential φ_0 is located at the distance L from the irradiated dielectric surface (Fig. 1b). Then, the potential of the dielectric surface can be found from the condition of continuity of the current in the drift region and the current in the dielectric:

$$\varphi_n = \frac{\left(\frac{\varphi_0}{L} + \frac{\varepsilon\varphi_a}{a}\right) + \left(\tilde{E}_n^{(0)} - \varepsilon E_n^{(0)}\right) - \frac{1}{\varepsilon_0}\rho_{su}}{\frac{1}{L} + \frac{\varepsilon}{a}}. \tag{8}$$

Here, $\tilde{E}_n^{(0)}$ and $E_n^{(0)}$ are the values of the electric field to the left and right of the dielectric surface, obtained by solving Poisson's equations in the drift region and in the dielectric for zero boundary conditions; $\rho_{su} = e\int_0^t [(J_P(E_n) + J_N(E_n)) - J^{(2)}(\tilde{E}_n)]\,dt'$ is the surface charge density; $\tilde{E}_n = \tilde{E}_n^{(0)} - (\varphi_n - \varphi_0)/L$; $E_n = E_n^{(0)} - (\varphi_a - \varphi_n)/a$; $J^{(2)}$ is the emission current from the exposed surface.

The emission current $J^{(2)}$ comprises the secondary electron emission and the field emission, which depends on the field in the drift region. It should be noted that, in calculating the field in the drift region $\tilde{E}$, the space charge field can often be neglected, i.e., $\tilde{E}^{(0)} \simeq 0$; however, one cannot always neglect the retarding of beam electrons in the field $\tilde{E}$.

Solution of the Equations. First of all, we shall perform the substitution of variables in Eqs. (1)-(6), introducing the range of fast electrons in the dielectric material R_0 as the length scale and $\tau_0 = (k_0 R_0/\alpha_0 I_0)^{1/2}$ as the time scale, where I_0 is the density of the incident current of particles, $k_0 = m_0c^2/\omega_i$, m_0c^2 is the energy of the electron rest mass, and α_0 is the characteristic recombination coefficient.

Then Eqs. (1)-(3) in dimensionless form are given by

$$\frac{\partial n}{\partial \bar{t}} = q + k_0 D - k_0 \xi n p - \frac{\partial j_n}{\partial z}; \tag{9}$$

$$\frac{\partial p}{\partial \bar{t}} = k_0 D - k_0 \xi n p - \frac{\partial j_p}{\partial z}; \tag{10}$$

$$\frac{\partial E}{\partial z} = E_A (p - n). \tag{11}$$

Here, n, p are the carrier concentrations, expressed in $I_0\tau_0/R_0$ units, j_n and j_p are the currents in I_0 units, $d\bar{t} = dt/\tau_0$, $d\bar{z} = dz/R_0$, $\xi = \alpha/\alpha_0$, $E_A = eI_0\tau_0/\varepsilon\varepsilon_0$, and q and D are the distributions of thermalized electrons and absorbed energy per incident particle in R_0^{-1} and m_0c^2/R_0 units, respectively.

Equations (9)-(11) together with (4) are solved numerically by repeated completion of steps with respect to time. The method of splitting the physical processes at the time step Δt is used for integrating Eqs. (9)-(11). Only the generation of charge carriers due to the ionization and thermalization of particles, as well as their decay due to recombination, are considered at the first stage. Solution of Eqs. (9) and (10) without the convective terms ($\partial j_{n,p}/\partial z = 0$) makes it possible to find the intermediate concentrations $\tilde{p}^{(j+1)}$ and $\tilde{n}^{(j+1)}$ in analytical form for the (j + 1)-th time step:

$$\tilde{p}_i^{(j+1)} = A_i^{(j)} \frac{1 - b_i^{(j)} \exp\left(-2k_0\xi_i A_i^{(j)}\Delta t\right)}{1 + b_i^{(j)} \exp\left(-2k_0\xi_i A_i^{(j)}\Delta t\right)} - \frac{1}{2}\left(\rho_i^{(j)} + q\Delta t\right),$$

$$n_i^{(j+1)} = \tilde{p}_i^{(j+1)} + \rho_i^{j+1} + q_i\Delta\bar{t},$$

where i is the node number in the three-dimensional grid;

$$\rho_i^{(j)} = n_i^{(j)} - p_i^{(j)}; \quad A_i^{(j)} = \left(D_i/\xi_i + \frac{1}{2}\left(\rho_i^{(j)} + q_i\Delta t\right)\right)^{1/2};$$

$$b_i^{(j)} = \frac{A_i^{(j)} - \left(p_i^{(j)} + \dfrac{\rho_i^{(j)} + q_i\Delta t}{2}\right)}{A_i^{(j)} + \left(p_i^{(j)} + \dfrac{\rho_i^{(j)} + q_i\Delta\bar{t}}{2}\right)}.$$

The effects of transport of charge carriers are calculated at the second stage, as a result of which the final values of particle concentrations at the (j + 1)-th instant of time are determined. This procedure is similar to that in [11]:

$$p_i^{(j+1)} = \tilde{p}_i^{(j+1)} - \frac{\Delta M_{i+1/2}^{(p)} - \Delta M_{i-1/2}^{(p)}}{h_{i+1/2}},$$

$$n_i^{(j+1)} = \tilde{n}_i^{(j+1)} - \frac{\Delta M_{i+1/2}^{(n)} - \Delta M_{i-1/2}^{(n)}}{h_{i+1/2}},$$

$h_{i+1/2} = (1/2)(z_{i+1} - z_i)$, and ΔM are the particle fluxes through the boundaries of adjacent cells.

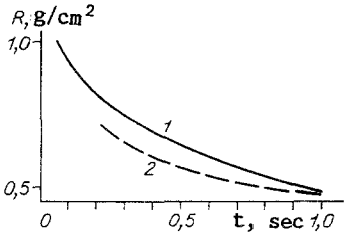

Fig. 2

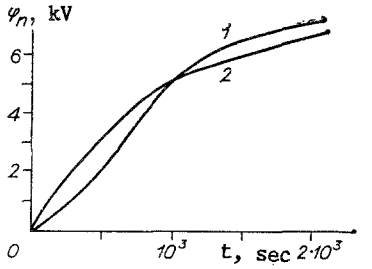

Fig. 3

The particle fluxes were calculated by using expressions of first-order accuracy:

$$\Delta M_{i+1/2}^{(p)} = \begin{cases} j_p\left(p_i, \dfrac{E_i + E_{i+1}}{2}\right)\Delta\bar{t}, & E_i + E_{i+1} > 0, \\ j_p\left(p_{i+1}, \dfrac{E_i + E_{i+1}}{2}\right)\Delta\bar{t}, & E_i + E_{i+1} < 0, \end{cases}$$

$$\Delta M_{i+1/2}^{(n)} = \begin{cases} j_n\left(n_i, \dfrac{E_i + E_{i+1}}{2}\right)\Delta\bar{t}, & E_i + E_{i+1} < 0, \\ j_n\left(n_{i+1}, \dfrac{E_i + E_{i+1}}{2}\right)\Delta\bar{t}, & E_i + E_{i+1} > 0. \end{cases}$$

The boundary conditions for the current, which were discussed above, are used in determining ΔM at the first and the last nodes.

The equation of the electric potential that follows from (3) is solved by means of the trial-and-error method at the third stage. The kinetic equation for fast electrons with the electric field (4) is solved at the fourth (last) stage by using the method described in [12]. In order to reduce the volume of calculations, the fourth stage is not realized at every time step, but only when the electric field strength changes by an amount which can cause considerable distortion of the flux. The time step $\Delta\bar{t}$ is equal to 0.005-0.1. The accuracy of the calculations is checked by calculating at each node the total current, whose value must not depend on the coordinate.

We find the electrophysical parameters of the dielectric by comparing the theoretical and experimental distributions. This also confirms the adequacy of the model. We shall provide calculations for two experimental situations: a) charging of shorted PMMA specimens with an electron beam with an energy of 1.3 MeV and a high current density, 10^{-6} A/cm² [13] (with such densities, steady-state operating conditions are not achieved because of electric breakdown) and b) charging of film specimens of F4-MBA fluoroplastic (Teflon) with an exposed surface. In the first case, due to the high density of the space charge, its electric field exerts a strong influence on the flux of decelerating electrons, and Eq. (4) is solved repeatedly. In charging specimens in a high-density flux, the most characteristic feature is the reduction of the mean free path of electrons due to the retarding action of the space charge field.

Figure 2 shows the behavior in time of the electron mean free path R in PMMA (1, calculations; 2, experiments [13]). The following values were used in calculations: The electron energy, the beam current, and the specimen thickness were the same as in the experiments; $\alpha = 10^{-15}$ m³/sec, $\omega_i = 100$ eV, $\mu_n^{(0)} = 5\cdot10^{-12}$ m²/(V·sec), $\mu_p^{(0)} = 0.1\mu_n^{(0)}$, $D_0 = 10^3$ rad/sec, and $\Delta t = 10^{-3}$. It is evident that the simulation of the process adequately reproduces the reduction of the mean free path.

In our experimental investigations of the electrification of F4 (Teflon) films with an exposed surface, we used a device comprising an electron microscope as a source of fast electrons. For the sensors, we used a current meter measuring the current from the electrode at the unirradiated rear side of the film and an electric field meter for measuring the field in the gap in front of the specimen, based on the electrostatic induction method. The entire device was placed in a vacuum chamber, which was evacuated to a pressure of 10 mPa. The aluminum electrodes on the unirradiated side of the specimen had a thickness of approximately 50 nm. The mass thickness of the films, $1.8\cdot10^{-2}$ g/cm², was determined by weighing. The diameter of the specimens was equal to 39 mm. The diameter of the irradiated spot (15 mm) was much larger than the film thickness, and we could assume that the irradi-

ation geometry was two-dimensional. The maximum density of the electron current was chosen so as to avoid electric breakdown. It was equal to $2 \cdot 10^{-9}$ A/cm^2. Figure 3 provides a comparison between the experimental 2 and the theoretical 1 behavior of the potential of the front (irradiated) surface φ_n as a function of the irradiation time for electrons with an energy of 40 keV and a current density of $5.6 \cdot 10^{-10}$ A/cm^2. The following values were used in calculations: $\mu_p^{(0)} = 5 \cdot 10^{-14}$ m^2/(V·sec), $\mu_N^{(0)} = 1 \cdot 10^{-14}$ m^2(V·sec), $\alpha = 10^{-15}$ m^3/sec, ω_i = 100 eV, and Δt = 0.01. Both dependences have the shape of curves with saturation at a potential of the order of 8 kV. There are small differences in the details of behavior. Calculations show that the emissive characteristics of the specimen's surface are the determining factor, while other parameters, such as the energy of carrier pair formation and the carrier mobility are secondary. As a result of emission, a positive charge is formed in the surface layer. The dependence of the emission current on the electric field strength of the type given by $t_{em} \cong i_0 \exp(\alpha\sqrt{E})$ was taken into account in calculations.

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